ELECTRON COOLING: REMEMBERING AND REFLECTING

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Abstract

The report contains a brief review of developments in electron cooling method. The influence of electron cooling concept on progress in particle beam physics is considered, particularly: development of alternative and complementary cooling methods – stochastic, laser, muon cooling; physics of cooled and intense particle beams; ordering effects in cooled ion beams and the idea of crystalline beam; intrabeam scattering in cooled beams, etc. Creation of new accelerator technology, based on electron cooling and its application to different fields of experimental physics – particle, nuclear and atomic physics – is described. Modern trends and new concepts of electron cooling application are discussed.

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REMEMBERING…

The history of invention, test and development of the electron cooling method provides many remarkable events and accomplishments. And this line begins, undoubtedly, with the first report of G. Budker at the Symposium in Sacley [1] in 1966. In that time Budker was thinking about a method of formation of dense (compressed) particle beams for proton – antiproton colliders. His idea of electron cooling was based on the model of electron - proton Maxwellian plasma. Then a few seminars followed, one of them was at SLAC.

Common opinion was: a nice idea… unfortunately - nonrealistic one… But such an argument was not for Budker, and in 1967 he decided to start the realization of the electron cooling project. For this purpose he had to concentrate manpower and therefore he closed, for instance, own project of the Relativistic Stabilized Electron Beam, which was in active stage. It was typical for Budker, who spoke frequently: "Fellows, don’t stick to your iron stuff!"

In 1968 a prototype of an electron cooler, called EPOCHA (from Russian "Electron Beam to Cool Antiprotons") was constructed. It became a test bench for testing the basic ideas proposed that time for an electron cooling device [2]: magnetized electron beam, electron energy recuperation, resonance optics, magnetic field formation (straight and toroidal solenoids), electron temperature measurement, and others.

In 1970 first real electron cooler aimed for electron cooling of protons was constructed and tested [3]. On a local slang it was for referred as "EPOCHA the Curve" – contrary to the prototype, which had no toroidal solenoids and was called, for this reason, as "EPOCHA the Straight".

In 1972 the designing of NAP-M - "Antiptoton Storage Ring – Model" (Russian) was begun (Fig.1). Soon it became "Sancta sanctorum" of electron cooling when in 1974 first electron cooling of protons was performed in this ring [4].

Fig.1. "Santa sanctorum" of electron cooling – the NAP-M storage ring.

The experiment parameters were the following: proton energy of 50 MeV, proton current 50 μA, electron energy 37 keV and electron current 100 mA. The measured equilibrium proton beam cross-section diameter of 1 mm (Fig. 2) and cooling time of 3 sec were consistent very well with Budker's theory.

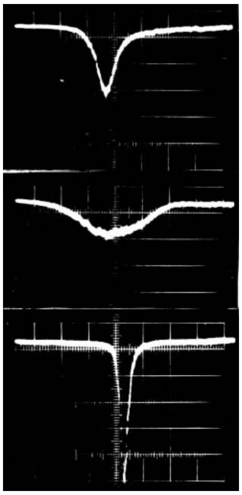

Fig.2. Proton beam density distribution at electron cooling measured with flying wire profilometer after acceleration (a), in 200 sec when cooling is off (b), in 1 sec after cooling is switched on.

However, in a year later, an improvement of cooler parameters – enhancement of electron energy stability and homogeneity of magnetic field, has given unexpected results: the betatron oscillation damping time at proton energy of 65 MeV and electron current of 0.8 A was measured equal to 83 ms, that was much shorter of "The Budker's numbers!" [5].

"The puzzle" of so called "fast electron cooling" was resolved soon: electron beam formed in magnetic field with electrostatic acceleration has specific characteristics - flattened distribution of electrons over velocities (in particle rest frame) and a weak sensitivity of electrons to a displacement across magnetic field in collisions with protons (electron beam "magnetization") [6]. But we understood the magnetization effect when experiment has shown it!

In 1977 – 79 "The Initial Cooling Experiment" was performed at CERN [7], and in 1979 – 82 "The Test Ring Experiment" at Fermilab [8]. N.Dikansky, I.Meshkov V.Parkhomchuk from Budker INP group participated in Fermilab experiment at its initial stage.

Detailed studies of the electron cooling mechanism were carried out in the single pass cooling experiment MOSOL ("MOdel of SOLenoid") at Budker INP in 1986 – 1988 [9]. It has given much better understanding of the cooling force dependence on parameters of the interacting beams.

Since 1988 "the era" of the second generation of cooler storage rings began. Few people remember a meaning of the abbreviations, which became now common names (Table1).

Table1. Electron cooler storage rings

Ring	Laboratory, country	Years of operation	Particles	Maximum energy [MeV/u, A / Z = 2]	Circumference [m]
NAP-M	Budker INP, USSR	1974-1984	p	1.5 – 85	47
ICE	CERN, Switzerland	1979-1980	p	46	74
Test Ring	Fermilab, USA	1980-1982	p	200	111
LEAR	CERN, Switzerland	1988-1999	$\bar{p}$	64	78.6
MOSOL (single pass cooling)	Budker INP, USSR	1986 - 1988	p, H^-	0.85	length 3 m
IUCF Cooler	Indiana Univ., USA	1988	A ≤ 7	500	86.8
TSR	MPI, Germany	1988	A ≤ 127	30	55.4
TARN-II	INS, Tokyo Univ., Japan	1993	A ≤ 20	100	77.8
CELSIUS	Uppsala Univ., Sweden	1989	A ≤ 40	340 (1360)	81.8
ESR	GSI, Germany	1990	A ≤ 238	30-560	108.4
CRYRING	MSI, Sweden	1992	A ≤ 238	0.3 – 24	51.6
COSY	FZ Juelich, Germany	1992	p	40 – 2500	184
ASTRID	Aarhus, Denmark	1993	Light ions	50	40
SIS	GSI, Germany	1998	A ≤ 238	2.0	216
HIMAC	NIRS, Japan	2000	He, C, Ne, Si, Ar	800	131.88
AD	CERN, Switzerland	2000	Antiprotons	2.76 GeV – 5.31 MeV	169.56
Electrostatic cooler ring at KEK	KEK, Japan	2002	C	0.02	8.1

A few are under construction presently: Recycler Electron Cooler (Fermilab, USA), two cooler rings complex (IMP, Lanzhou, China), Low Energy Ion Ring (CERN), TARN-II–renovated (RIKEN, Japan), S-LSR (Kyoto University, Japan).

REFLECTING…WHAT WAS DONE WITH ELECTRON COOLING APPLICATION?

What is "a harvest"? It is very rich. One can say that now electron cooling of all the elements of The Mendeleev Periodic Table and antiprotons was accomplished. As significant achievements one can regard many experimental results obtained at cooler rings.

1) Particle physics.

Experiments with cooled and extracted slow antiprotons at LEAR (CERN) have brought a new knowledge in particle physics. Among them, as an example, one can point out the experimental discovery of so-called Okuba – Zweig – Iizuka rule violation, in $p\bar{p}$ interaction at low energy, which proved a complicated structure of nucleons [10].

Important results were achieved in particle physics of middle energy ("mezon physics") with protons of 1 – 2 GeV energy interacting with a target at three storage rings – IUCF, COSY and SELSIUS. These experiments are in progress. One should note here the idea of superthin target application in a cooler ring outspoken much earlier [11].

2) Nuclear physics.

Physics of radioactive nuclei and rare isotopes, studies of exotic nuclei states are carried out with cooled ion beams at ESR and SIS (GSI). High precision mass measurements of 500 isotopes with accuracy $\Delta M/M \leq 2\cdot 10^{-7}$ were accomplished at ESR. 200 of these mass values were unknown before.

3) Atomic physics.

New stage of experiments in atomic and molecular physics became possible owing to electron coolers TSR, CryRing, ASTRID. The cooling electron beam is used in this rings as an electron target, which allows to study ion-electron interaction at pure vacuum conditions.

4) Antihydrogen generation.

First antihydrogen was generated in-flight with stochastic cooling application at LEAR in 1996. Later commissioning of AD cooler ring at CERN made possible to set up two experiments with antihydrogen ($\bar{H}$) generation at rest – ATHENA and ATRAP. Both of them reported obtaining first $\bar{H}$ atoms in 2003. Here electron cooling in traps is used as an efficient tool.

5) "Nonliouvillean" particle beam physics.

The creation of the electron cooling method initiated a significant progress in the particle beam physics. One can say now about formation of "the cooling ideology". Before only cooling method known as "the radiation damping" existed actually. It played a key role in very first electron – electron colliders. After electron cooling invention a few other cooling methods were sent on a stage. Stochastic cooling (S.Van der Meer, CERN) provided a success of $p\bar{p}$ collider and discovery of W± and Z_0 bosons at CERN. Laser cooling (with "an aid" of electron cooling) was realized in TSR, ASTRID and ESR. Muon cooling, proposed by A. Skrinsky, is under development and remains to be the main hope for muon collider.

Effect of a sudden reduction of an ion beam momentum spread during electron cooling discovered in NAP-M [12] was studied in details in ESR, SIS [13] and CryRing [14]. It was interpreted as a beam ordering (“crystallization”) and recently three dimensional crystalline beams were obtained in traps and in the "table-top" storage ring PALLAS (LMU, Munich, Germany).

The particle beam physics was extremely enriched by initiation of the further development of such problems as stability of intense and dense (cooled!) particle beams in storage rings, intrabeam scattering in cooled beams, physics of crystalline beams, stability of a particle beam in storage ring in presence of an internal target, beam-beam effects in colliders at a cooling presence, etc.

REFLECTING…WHERE WE ARE AND WHERE WE GO…

Physics of electron cooling

Theory of electron cooling is well developed nowadays. However, the problem is very multiparametric that calls for application of numerical simulation. A great progress was achieved in this area of research. Among several computer codes devised specifically one can point out the BETACOOL [15] code for numerical simulation of electron cooling process in storage rings (developed by our group at JINR). It combines analytical calculations with molecular dynamics simulations taking into account a ring lattice, vacuum conditions, space charge of both interacting beams, IBS in the ion beam, internal, target, etc.

An essential progress was achieved during recent years in understanding of physics of cold intense beams. The "old" opinion existed before said: an ion beam can be cooled effectively, if it has

- at stochastic cooling – large emittance and low intensity;
- at electron cooling – small emittance and even (indifferently) high intensity.

The question - what is a beam intensity limit at electron cooling? – was not answered clearly.

The "new dish" has appeared "on the table" when "electron heating effect" was observed and studied in SELSIUS: ion beam current is limited by "two beams instability" [16].

Further studies at COSY have shown that the proton stack intensity at electron cooling is limited by the two stage instability: the effect of nonlinear electric field of electron beam on protons and development of coherent instability of cooled proton beam [17].

The next reason, which provokes an ion beam instability in a cooler ring has been found at HIMAC: residual gas ions stored in the cooling electron beam [18] play a role of "a memory" for fluctuations of the beam space charge. It was confirmed in COSY (June 2004).

This brings up again an "old" question: do we need electron beam neutralization? We have the definite answer now. "No" - if we deal with an intense ion beam (especially a beam of heavy multicharged ions); then neutralization has a harmful effect . And "yes" if we have to form a cold and well compressed ion or antiproton beam of a modest intensity.

Electron cooling engineering

Electron energy range of modern electron coolers extends today from 10 eV (KEK) to 400 keV (Budker INP/IMP, Lanzhou).

"Tomorrow" we expect commissioning of electron cooler of the electron energy of 4.4 MeV at Fermilab [19]. And "after tomorrow" the project of electron cooler for RHIC on the electron energy of 54.5 MeV (100 GeV/amu ions) is under development by collaboration of Budker INP and BNL [20].

New concepts in electron cooling "technologies"

Several new concepts of electron cooling application have appeared "on horizon".

1. Electron cooler based on electrostatic accelerator of electron energy of 7 MeV proposed by BINP for High Energy Storage Ring (HESR) in FAIR project at GSI is aimed to cool antiprotons up to energy of 14 GeV. This concept assumes a new scheme of electrostatic accelerator with "magnetized" electron beam [21].
2. Electron cooler with bunched and single pass electron beam – the scheme based on recuperator-linac (proposal BINP for RHIC, see above).
3. A scheme of electron-ion collider with crystalline ion beam having very high luminosity has been proposed recently [22].
4. The scheme of "Single particle cooling" elaborated by GANIL/JINR collaboration [23] enables to store rare radioactive ions in a storage ring with electron cooling [22].
5. New scheme of the storage ring with longitudinal magnetic field is under development at JINR (the LEPTA Project) [24]. This machine being constructed makes possible to realize electron cooling of circulating positrons and Positronium generation in-flight, antihydrogen generation and electron cooling of high energy ions and antiprotons with circulating electron beam.

CONCLUSIONS

1. Electron cooling became nowadays an efficient tool of low energy heavy particle (ions, antiprotons) beams formation in storage rings.
2. Particle beam physics has been enriched significantly with development of electron cooling method and its application to formation of intense and dense heavy particle beams.
3. Expansion both into the range of middle and high particle energy and, into the range of extremely low energy allows to construct radically new facilities which have many applications in particle, nuclear and atomic physics.

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